

BOEING'S HIGH VOLTAGE SOLAR TILE TEST RESULTS

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Abstract

Real concerns of spacecraft charging and experience with solar array augmented electrostatic discharge arcs on spacecraft have minimized the use of high voltages on large solar arrays despite numerous vehicle system mass and efficiency advantages. Boeing's solar tile (patent pending) allows high voltage to be generated at the array without the mass and efficiency losses of electronic conversion. Direct drive electric propulsion and higher power payloads (lower spacecraft weight) will benefit from this design. As future power demand grows, spacecraft designers must use higher voltage to minimize transmission loss and power cable mass for very large area arrays. This paper will describe the design and discuss the successful test of Boeing's 500-Volt Solar Tile in NASA Glenn's Tenney chamber in the Space Plasma Interaction Facility. The work was sponsored by NASA's Space Solar Power Exploratory Research and Technology (SERT) Program and will result in updated high voltage solar array design guidelines being published.

I. Introduction

The power source for virtually all satellites is photovoltaic solar arrays. They are critical to the satellite's operation and often are a limiting parameter in a satellite's mission capability and operational lifetime. The solar array's intrinsic fragility, exposure to harsh free-space environment, and a desire for minimizing solar array mass, stowage volume, and deployed area all place severe constraints on solar array design. As future power demands grow spacecraft designers must use higher voltage to minimize transmission loss and power cable mass for very large area solar arrays. Spacecraft mass and cost sensitivity encourages large area solar arrays to generate as well as distribute high-voltage.

High-voltage, high-power arrays in various earth orbits are subject to continuous arcing, which can destroy conductors and lightweight substrates. Arcing can become catastrophically augmented by solar array string currents to physically destroy solar array strings. Space plasma charging, auroral charging, electrodynamic effects, and sputtering or electron heating cause discharge arcs that waste power and can lead to power surges and solar array destruction. In the past 5 years, the loss of several spacecraft from on-orbit solar array failures and more recent evidence of electrostatic-discharge-induced, solar array augmented, arc failures demonstrates the importance of robust high voltage solar array design. Recently, interactions between high voltage solar arrays and their space environment has led to an increased understanding of spacecraft charge arcing on the solar array. Higher spacecraft cost, longer duration environmental exposure, and higher mission criticality has resulted in a higher reliability requirements being placed on each subsystem. Designers have (correctly) responded with more conservative approaches including lower voltages, below Paschen Law voltages, or by incorporating added system elements, such as the plasma contactor to "ground" the Space Station. This paper reports on one of an increasing body of work that pushes technology to solve the high voltage design issue.

II. Project Overview

The work reported here is a result of collaboration between engineers at NASA Glenn Research Center and Boeing, Seattle working under NASA's Space Solar Power Exploratory Research and Technology (SERT) Program. SERT focused well beyond 100kW to develop enabling technologies for new applications in space science, exploration, and commercial applications. Specifically, space solar power (SSP) generation and transmission to earth electric power users. The economic viability of very high power in space depends on the successful development of various new technologies, such as high-voltage solar arrays. These solar arrays are not only required for SSP, but could also be used for large high-power spacecraft, distributed spacecraft concepts, solar electric propulsion systems (SEPS), space-based radar, and space-based laser systems. This contract entitled "Advanced High Voltage Solar Array Design Guidelines from Solar Tile Testing" uses a Boeing solar tile design to characterize and extend high voltage design guidelines for the industry. Specifically, The Boeing/GRC team used a previously produced 34-Volt solar tile (ST) to perform plasma interaction tests using the NASA GRC Tenney vacuum chamber in the Plasma Interaction Facility. The results were used to design a high voltage tile. A new 500V solar tile was designed and manufactured, and has been tested in the Tenney chamber. These results will be used to update the solar array design guidelines. This paper reports the test results prior to the development and publication of those design guidelines.

III. Solar Tile Features

Boeing's solar tile, typically about 1 ft², features tightly packed, multi-junction solar cells, under a common coverslide, interconnected with Kapton[®]/copper flexible circuitry. Robotics allows solar cells to be rapidly and precisely placed, with very small cell-to-cell gaps, resulting in a very high cell packing factor (98%). Batch vapor phase soldering simplifies cell interconnection; development of coplanar cell contacts allows use of Kapton[®]/copper flexible circuitry instead of fragile discrete interconnects. Along with lower fabrication cost, the single coverslide provides superior plasma charge, atomic oxygen, and radiation protection during on-orbit operation. The solar tiles can be produced over a wide range of voltages and sizes, using various solar cell types. In addition to supporting standard spacecraft voltages, the tiles are ideally suited for high-voltage applications such as direct-drive electric propulsion. Since the solar tiles can be built to supply full bus voltage, the power ratings for the solar arrays can be achieved by connecting the required number of solar tiles in parallel.

Because it's single coverslide covers entire (bus voltage) circuits and it's coverglass is conductively coated and grounded, the Solar Tile offers excellent protection to high voltage arcing and from any environmental interaction. It is "cell-technology independent", utilizes high production-rate robotics cell placement for low assembly and no tooling cost. Boeing's Solar Tile concept is shown in figure 1. It illustrates the front and rear side of a typical solar tile. Mechanical cells were used in this early production version. It has been low-earth orbit qualified in acoustic, shock, thermal cycle and thermal vacuum cycling tests.

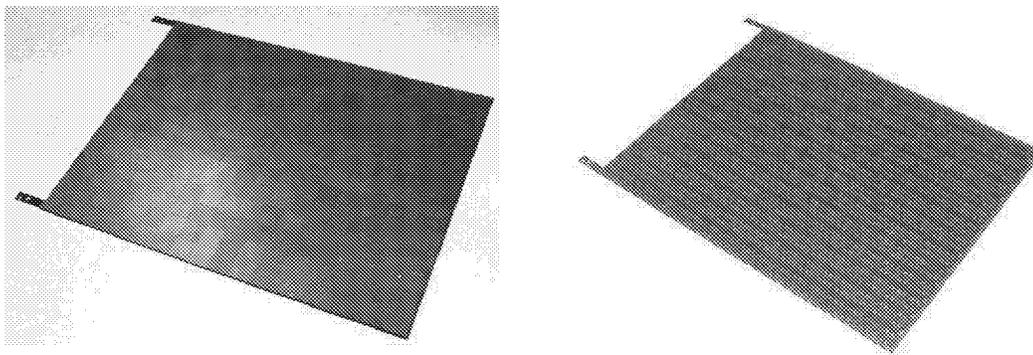


Figure 1: Front and Back views of a typical solar tile

IV. Methodology

The Boeing/GRC team utilized models of the existing 34V solar tile design to assess high-voltage susceptibility. A NASA Glenn team then performed plasma interaction tests on the Solar Tile using the NASA GRC Tenney vacuum chamber in the Plasma Interaction Facility. During testing, we will introduce a high-voltage electrostatic discharge (ESD) event-driven failure of the high-voltage solar tile. A fast switching shunt or other undefined device may be able to isolate or discharge the failure mechanism before the fault has a chance to cause permanent damage. Figure 2 shows the test facility. The background chamber was used and had the physical test setup as shown in Figure 3.

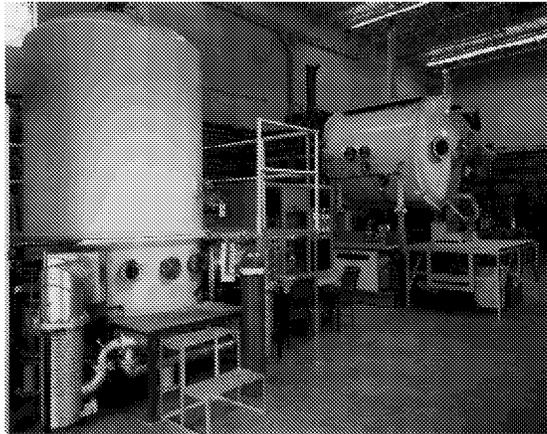


Figure 2. The Tenney Plasma Interaction Facility

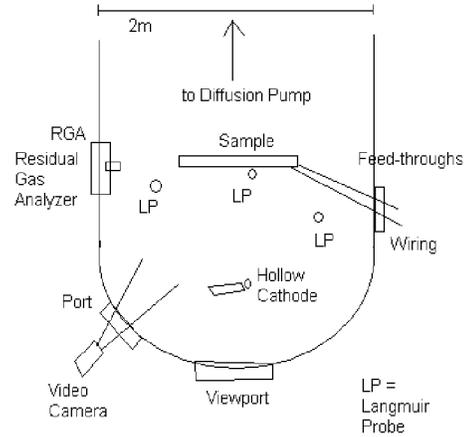


Figure 3. Chamber Test Setup

The results were used to expand and update our knowledge regarding high-voltage solar array design guidelines. The Boeing/GRC team tested the existing 34V solar tile design to assess high-voltage susceptibility. The Solar Tile design features of a large single conductively coated coverslide, large coverslide overhang. Coverglass grounding to the substrate provide a substantial improvement to high voltage solar array space environment tolerance. It is pictured in Figure 4.

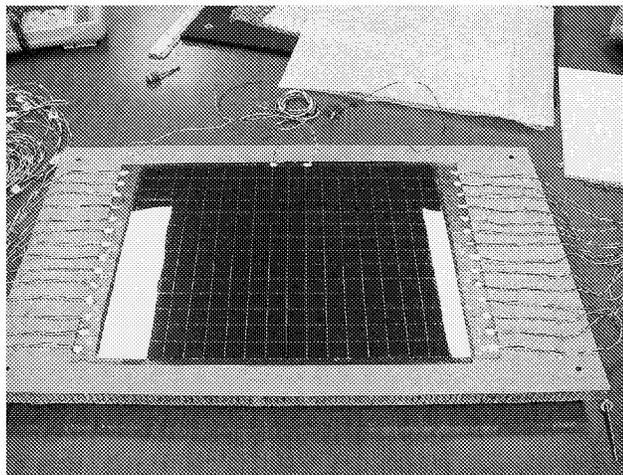


Figure 4: The 34-volt Test Article

The test article is a single solar tile measuring 11 by 14 inches mounted on a lightweight rigid substrate. There were four overhang dimensions on the test article, and the least damage at very high plasma voltage exposure was the largest overhang. The overhang was “filleted” to the substrate with coverglass bonding adhesive in each case.

V. Test Results

The plasma test results with high offset cell string voltages indicate that these 34-volt solar arrays will work at the -850-Volt plasma voltage. Two isolated plasma flashovers occurred up to -950 volts and continuous arcing commenced around -1000volts.

The observations during testing can be summarized as follows. The 34-Volt test sample arced once at -300 V on right-hand coverslide edge. Later, the sample arced once at -650 V somewhere on right hand coverslide (flash was so bright it blinded the video). In over six hours of additional testing at voltages between -300 V and -950 V, no arcs occurred anywhere. At -1000 V, numerous small arcs occurred at the edge of the kapton backing Currents between biased and unbiased strings were greater than anticipated, although no arcs were seen. When biased at -1000 V, cells in many solar array strings glowed from forward bias current.

It must be noted that the coverslide lay-up not standard, left side of coverslide cracked under rapid vacuum pumpdown. Figure 5 shows the coverslide crack and the -650V arc event sites.

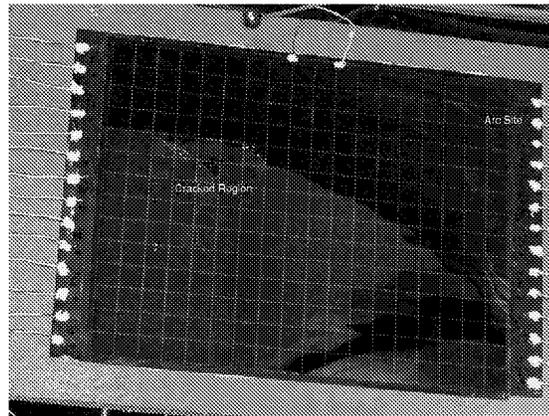


Figure 5: 34-Volt Tile after plasma testing

An extensive development effort isolated the multiple root causes. Boeing built many samples and tiles to both demonstrate causality and to verify the process steps needed to prevent the reoccurrence and “qualified” the new manufacturing steps and resulting tile. The new steps were incorporated into the 500-Volt solar tile processing and no coverglass debonding or cracks occurred at any time. Figure 6 shows the 500-Volt tile.

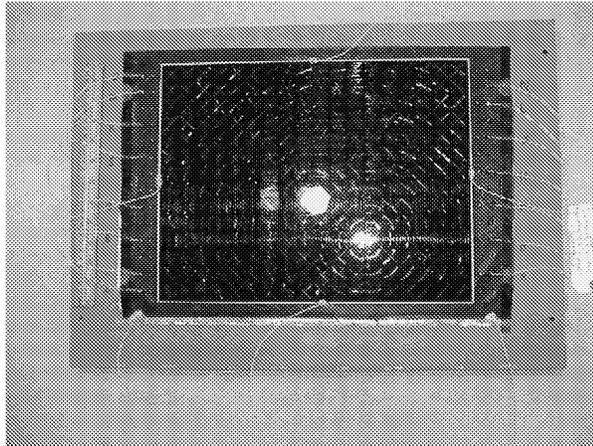


Figure 6: 500-Volt solar tile prior to plasma testing

The results of the 500-Volt Solar Tile test are summarized as follows. The sample arced once at -600 Volts. Figure 7 shows the sequence of four video frames that show the arc occurrence at -600 Volts. The top left frame is the pre-arc condition and the three other frames show the flashover and quench in clockwise direction. Some halo discharges became visible at approximately -750Volts. Leakage current was observed on the face of the Kapton®/copper flex circuit. No electrical performance degradation was measured or physical damage observed following exposure up to the (approximate) -1100Volt test limit.

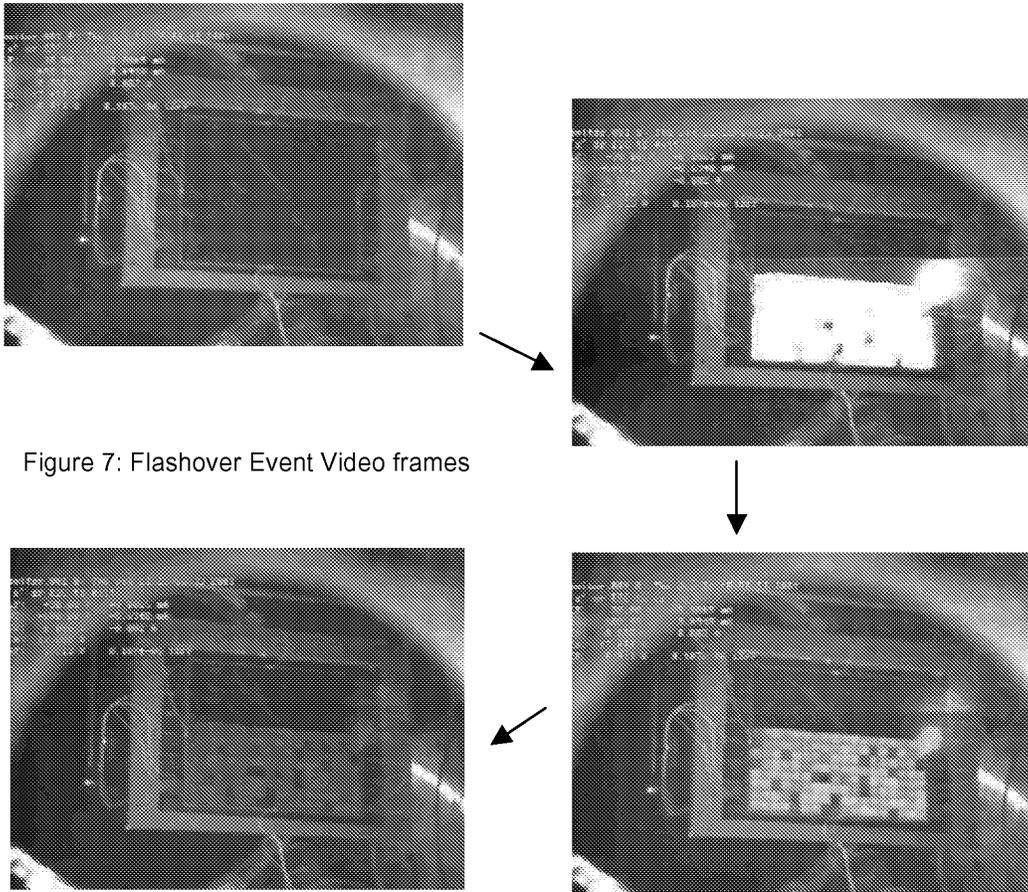


Figure 7: Flashover Event Video frames

VI. Conclusion

In conclusion, the high voltage solar tile design exceeded our 500-Volt testing goals because the solar tile withstood a worst-case low earth orbit (LEO) potentials between surfaces of the solar tile using simulated space plasma in GRC Plasma Interactions Facility. Determined the arc thresholds for Solar Tile at voltages of 600 V or more, relative to the plasma. We demonstrated 500-Volt solar tile tolerance to plasma charging

The one-time arcs may be attributed to H₂O evolution from adhesive or defect burning because they only occurred once.

Lastly, the solar tile is “flight ready” for direct drive electric propulsion applications.

In summary, the design and successful test of Boeing’s 500-Volt Solar Tile in NASA Glenn’s Plasma chamber indicates that the road to very high space power and direct drive electric propulsion is clearly open to further successful development.